Spectrally-Presaturated Modulation (SPM): an efficient fat suppression technique for STEAM-based cardiac imaging sequences

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I. INTRODUCTION

Cardiac MR imaging using Stimulated Echo Acquisition Mode (STEAM) sequences [[1], [2]] is drawing increased interest due to the potential for determining the myocardial function. The basic idea of STEAM sequences is to initially apply a spatial modulation (or encoding) of magnetization. Then, a demodulation (decoding) of the magnetization is applied immediately before each subsequent image acquisition in order to achieve a stimulated echo. It is worth noting that the modulation is just a temporary phenomenon that fades exponentially due to T1-relaxation [[1],[2]].

The high speed of cardiac motion necessitates fast acquisition in order to track the myocardium throughout the different cardiac phases. Speeding up the temporal resolution of STEAM–based sequences was the focus of a number of researchers [[4]-[7]]. Nevertheless, a considerable loss in temporal resolution is inevitable in these techniques when fat signal is to be suppressed. Spectral-Spatial Selective Pulses (SSSP) Technique [[8]] is a common fat suppression technique in cardiac function imaging. The technique is based on modifying each excitation RF pulse so that it selectively excites the water contents of the image voxels (see Figure 1(a)). Unfortunately, the SSSP technique is accompanied by an increase in the acquisition repetition time (TR). Another alternative such as Spectral Pre-Saturation Inversion Recovery (SPIR) technique [[8]] is not suitable for cardiac imaging. The reason is that repeating a pre-saturation pulse before each excitation RF pulse, besides reducing the temporal resolution, increases the SAR level and reduces SNR as will be shown later.

In this work, we present a fat suppression technique for STEAM-based sequences. The technique applies a pre-saturation pulse, similar to that used in the SPIR technique, prior to modulating the magnetization (hence, the name: Spectrally-Presaturated Modulation (SPM)). Consequently, only water, but not fat, is modulated and thus water signal can be acquired selectively during image acquisition.

II METHODS

Pulse Sequence

Figure 1(b) shows the pulse sequence of the proposed technique of fat suppression. As shown in the figure, a spectrally selective pre-saturation pulse is applied before the modulating RF pulses. The resonance frequency of the presaturation pulse is tuned to excite only the protons of the tissue fat. Ideally, the flip angle of this pulse should be 90^o, so that no fat magnetization is available at the time of modulation. However, a slightly larger value $\alpha = \cos^{-1}(1 - e^{-t_{inv}/T_1})$ is used to account for the T1 relaxation of fat magnetization during the period, t_{inv}, between the pre-saturation pulse and the modulation pulse. The interval, t_{inv}, is determined by the required suppressed spectrum around the fat resonance frequency plus the minimum time of the spoiler gradient. It is important to note that although there is no longitudinal magnetization component of the fat at the time of the modulation pulse, the transverse component still exists. Therefore, spoiling of the transverse component is required in order to avoid refocusing of the fat magnetization by the subsequent gradients.

Phantom Experiments

A phantom consisting of a bottle of water placed beside a bottle of baby oil (fat) was used to test the proposed fat suppression technique and compare it to the other available techniques. Two STEAM-based MR imaging applications are considered in this work: 1) CSPAMM [[9],[10]], and 2) Black-blood cine STEAM [[2],[11]]. Fat suppression in these two applications was achieved using: 1) Spectrally-Presaturated Modulation (SPM), 2) spectral-spatial selective pulses (SSSP) using a 1-3-3-1 combination of RF pulses [[12],[13]], and 3) spectral presaturation with inversion recovery (SPIR) [[14]]. The experiments were done on a 1.5 Tesla scanner (Intera, Phillips Medical Systems, Best) using spiral acquisitions. The imaging parameters were: spiral acquisition window=12ms; 12 interleaves; slice thickness=10mm; 19 cardiac phases; and rectangular FOV=350mm. A ramped flip angle with a maximum=40^o was used to maintain the signal of the stimulated echo fixed throughout the different acquisitions [[10]]. The TR/TE for the SSSP, SPIR, and SPM were 22.3/4.5, 31.5/1.1, and 15/1.1 ms, respectively. The modulation frequency for the CSPAMM and the STEAM pulse sequences was 0.125 mm^{-1} and 0.3 mm^{-1}, respectively.

III. RESULTS

Fig. 2 shows the results of imaging the water and oil bottles using CSPAMM. As shown in the figure, the SPIR technique, while suppressing the oil bottle significantly, still shows remnants of a tagged region inside the oil bottle (arrow head). On the other hand, the SSSP and the SPM techniques were equally successful in suppressing the fat signal. Fig. 3 shows

the results when the same phantom was imaged using the black blood STEAM technique. Although both the SSSP and SPM techniques managed to suppress the fat signal, the SPM technique showed more uniform intensity for the water bottle than did the SSSP technique. On the other hand, the SPIR technique generated a bright spot artifact inside the center of the water bottle. Fig. 4 shows the signal-to-noise ratio (SNR), calculated as the intensity average divided by the standard deviation inside the region of interest (indicated in Fig. 3(a)). It can be seen that the SNR of the SPM is the highest among all the techniques throughout the different cardiac phases.

IV. DISCUSSION

The results shown above verified the potential of the SPM technique as an efficient method of fat suppression in many STEAM-based MR applications. The high temporal resolution provided by the SPM technique has many advantages for cardiac imaging. First, it increases the number of cardiac phases that can be captured. The imaging parameters described above allowed the acquisition of 40 cardiac phases for the SPM compared to 19 and 28 for the SPIR and the SSSP, respectively. Second, deformation imaging at high temporal resolution improves the performance of the algorithms that track myocardial motion from CSPAMM images. As shown in Fig. 4, the SPM technique has the highest SNR among the considered fat suppression techniques. Moreover, the SNR does not drop with time as it does in the SSSP and SPIR techniques. This is mainly because in SPM, only one fat suppression pulse is applied at the beginning of the sequence compared to the repeated application typical of the other techniques. To illustrate this, assume that a ratio, r, of the water magnetization is mistakenly suppressed because of the application of one imperfect fat suppression pulse (due to bad shimming or field inhomogeneity) [[8],[15]]. In this case, the SNR reduction factor at the n^{th} acquisition would be r in SPM and r^n in the other two techniques.

In addition, due to the elimination of the extra fat saturation pulses before each excitation RF pulse, the specific absorption ratio (SAR) of the SPM is significantly reduced compared to that of the SPIR. In the results displayed above, the SAR level for the SPM, SPIR, and SSSP techniques were 0.2, 0.37, and 0.15, respectively. The reason for the low SAR of the SSSP technique is the division of the excitation RF pulse into a series of four RF pulses. This, however, increases the TE time (4 times that with SPM or SPIR), which makes the pulse sequence more vulnerable to field inhomogeneity and motion artifacts.

V. CONCLUSION

An efficient technique has been presented for suppressing the fat signal in a number of MR STEAM-based imaging techniques. The technique improves the temporal resolution of the acquisition without sacrificing the SNR, SAR, or scan time.

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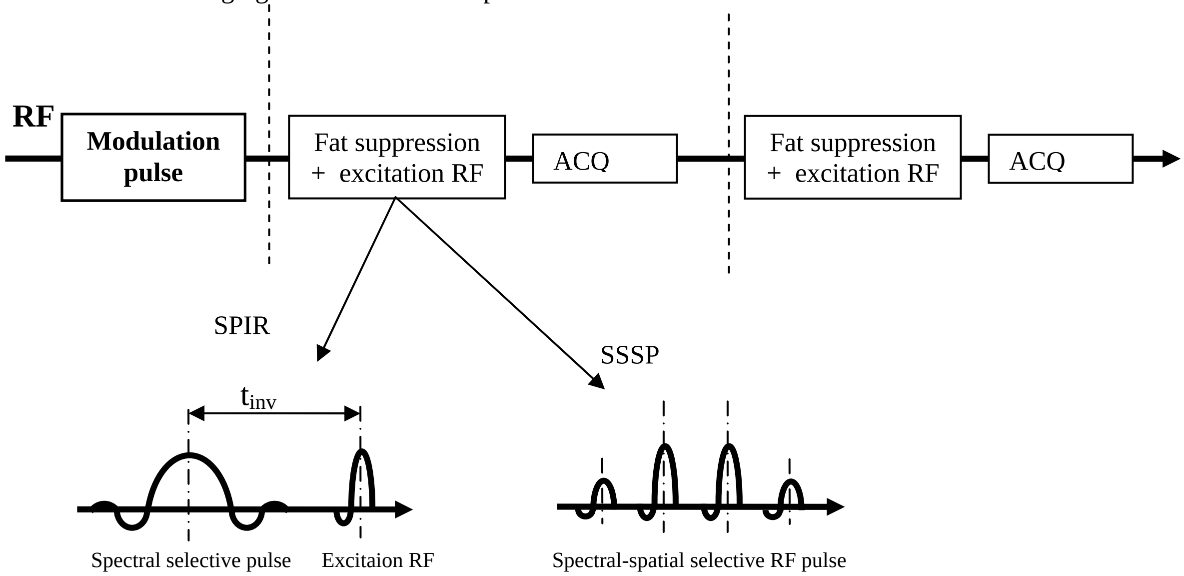
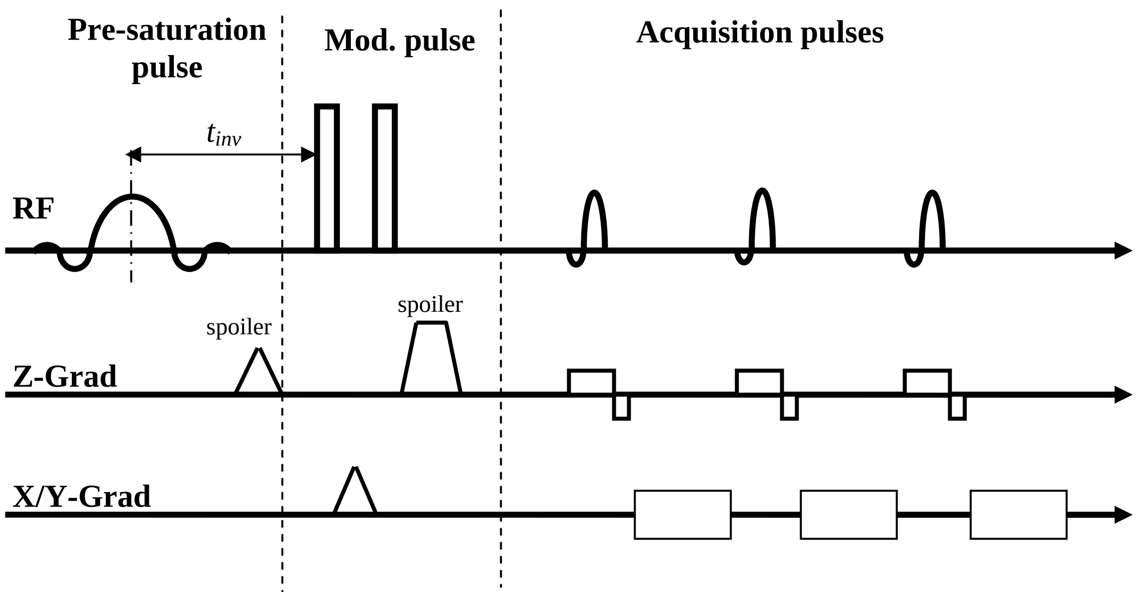


(a)



(b)

Fig. 1 Basic SPAMM pulse sequence with fat suppression. (a) According to the fat suppression technique used, the excitation pulse can be preceded with a spectral (fat) selective pulse, or it can be disintegrated to a series of non-selective smaller RF pulses. (b) The modulation pulse is preceded by a spectral (fat) selective pre-saturation pulse, and hence, no fat magnetization is available when applying the modulation pulse.

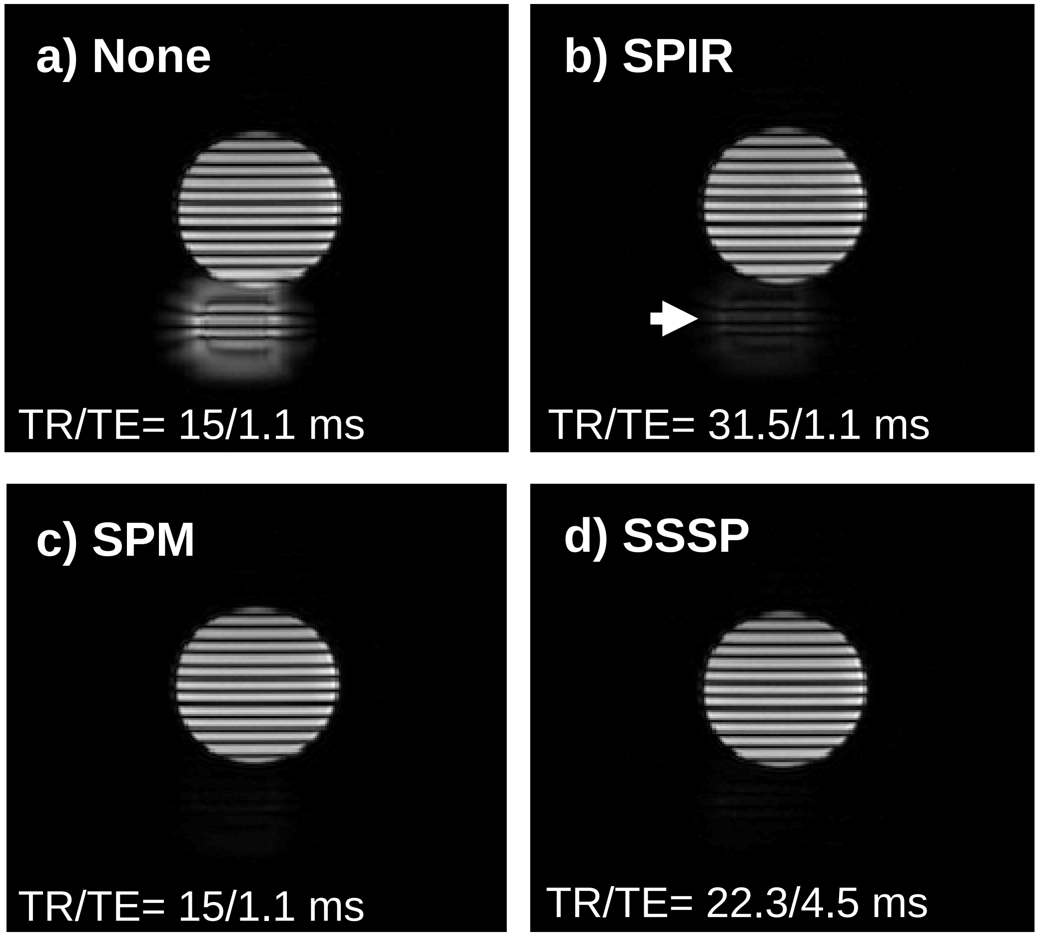


Fig. 2 CSPAMM images of a water bottle with a bottle of baby oil placed beside it. The arrowhead in image (b) shows that the SPIR has not completely suppressed the fat signal.

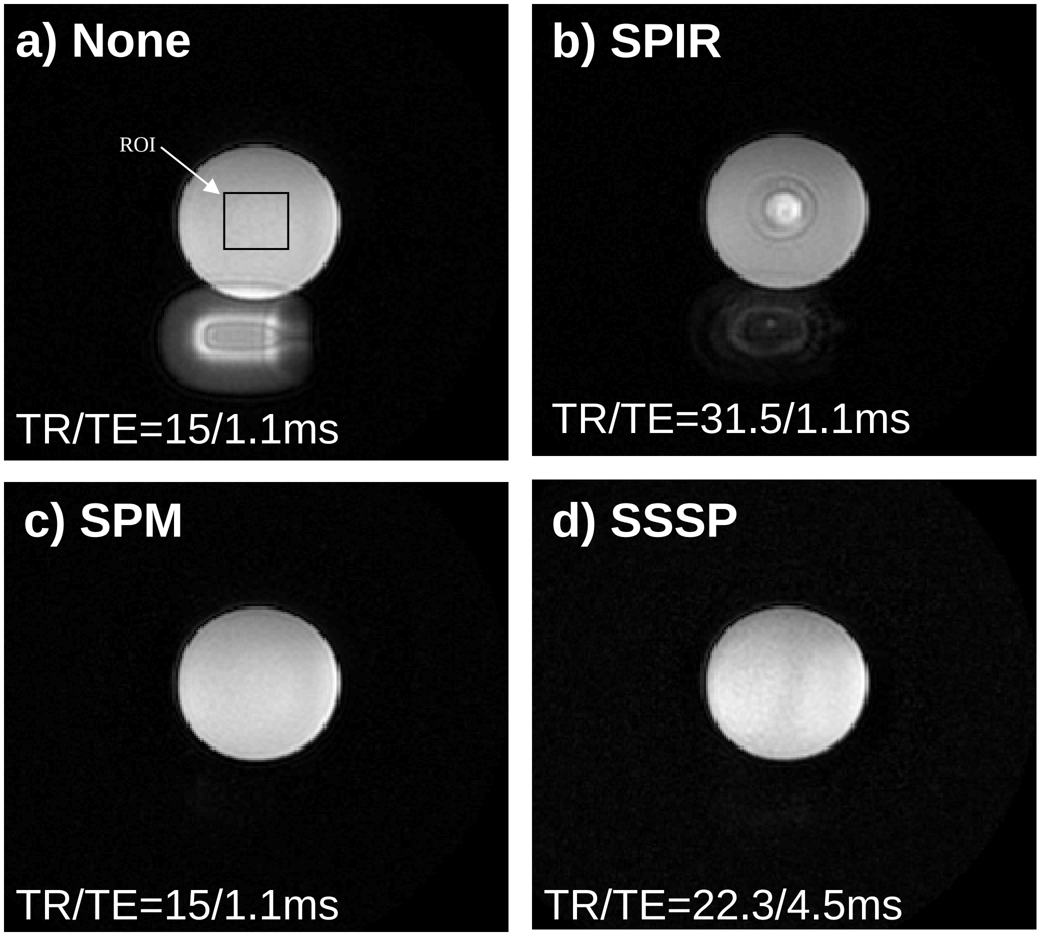


Fig. 3 black blood STEAM MRI images of a water bottle with a bottle of baby oil placed beside it.

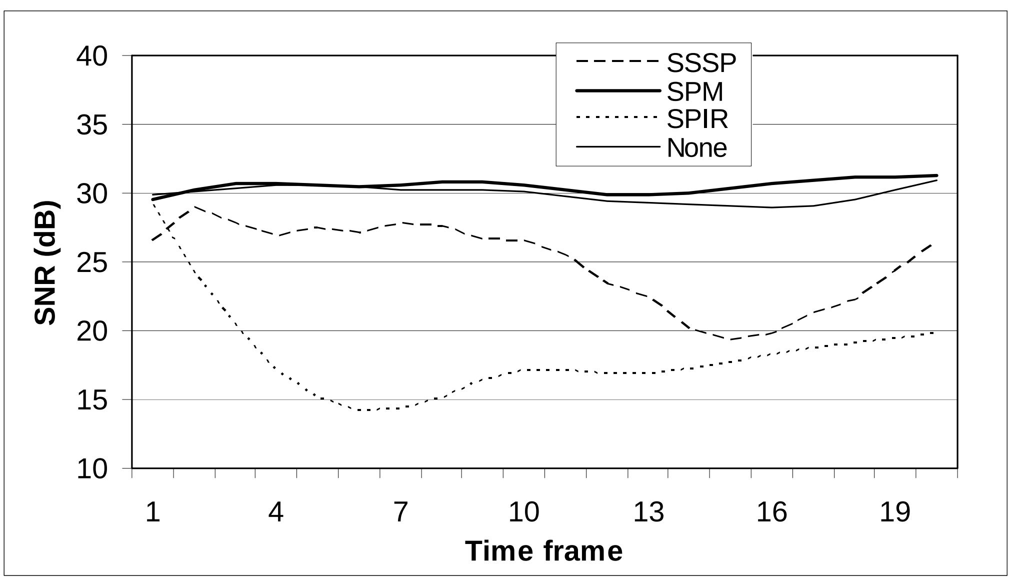


Fig. 4 The SNR calculated for the different cardiac phases inside the region of interest (ROI) indicated by the rectangle in Fig. 3.a.